Gilbert (G.K.)

Dr J. J. Woodward
with regards of
G. K. Gilbert

THE COLORADO PLATEAU REGION

CONSIDERED AS

A FIELD FOR GEOLOGICAL STUDY.

BY

G. K. GILBERT,
Washington, D. C.

[FROM THE AMERICAN JOURNAL OF SCIENCE AND ARTS, JULY AND AUGUST, 1876.]

NEW HAVEN:
TUTTLE, MOREHOUSE & TAYLOR, PRINTERS.
1876.

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THE COLORADO PLATEAU PROVINCE AS A FIELD FOR GEOLOGICAL STUDY.

I. *Definition and Description of the Province.*

IN the Mississippi Valley and "the Plains" the strata are almost undisturbed and lie nearly level. They have, indeed, been lifted above the parent ocean, and in part raised to a height of thousands of feet, but broad areas have moved together and all flexures have been gentle. There are no traces of the foldings which characterize the Appalachian region. The prevalent features of topography are plains and hills.

From the western edge of the plains to the Pacific Ocean the characteristic features are mountains. The strata are bent and broken, and upturned at all angles. The typical structures are structures of displacement. Within this region of great disturbance is a restricted area of comparative calm. Dislocations of strata are not unknown in it; indeed they are of frequent occurrence; but they are less frequent, less profound, and less complex, than in the surrounding region of mountains. Its mountains are few and scattered, and its typical topographic form is the table or plateau. It is called the Colorado Plateau Province.

This region of plateaus was crossed by many lines of early exploration, and the salient features of its topography were described by numerous observers. The first writer who called attention to the extent of the district, and colligated the northern portions with the southern, was Professor W. P. Blake (Pac. R. R. Repts., vol. iii, part IV, pp. 8 and 42, 1856.) The title of "Colorado Plateau" first appeared in the map of Ives' Colorado River Report in 1861, and was written between San Francisco Mountains and the Grand Cañon. Later usage extended the term to include the broad upland through which the Colorado has excavated its deep channel; and finally, as the minor plateaus of which the great one is composed began, in the progress of geographical knowledge, to be discriminated and named, the comprehensive title of the whole became *the Colorado Plateaus* or *the Colorado Plateau Province.* Portions of the region have been studied, described, and mapped by numerous geologists and geographers, but the chief contributions to our knowledge of the province as a whole, and of its limits, have come from the surveys conducted by Major Powell and Lieutenant Wheeler.*

* Exploration of the Colorado River of the West and its tributaries; by J. W. Powell. Washington, 1875.

U. S. Engineer Explorations and Surveys west of the 100th meridian, vol. iii, Geology; by G. K. Gilbert, Archibald R. Marvine, Edwin E. Howell, and J. J. Stevenson. Washington, 1876.

It would avail little to describe in detail the boundaries of the province without the aid of a map. On the east it is separated from the plains by a continuous broad belt of mountains, which include the parks of Colorado and have been called the Park Mountain System. On the south and west it adjoins the Basin Range Province, a region of many short parallel ranges, separated by trough-shaped, desert valleys. Northward it is limited by mountains for which there is no comprehensive title. Its greatest extent from north to south is 700 miles; from east to west, 425 miles. It comprises, of southern Wyoming, 20,000 square miles; of eastern Utah, 50,000; of western Colorado, 30,000; of northeastern Arizona, 45,000; and of northwestern New Mexico, 25,000;* making a total of 170,000 square miles, or one-twenty-fourth part of the territory of the United States. It is drained chiefly by the Colorado of the West and its tributaries, but the Sevier river heads in the western margin, and the Puerco of the East in its eastern, and the North Platte drains its northeastern angle. The plateaus which compose it range in altitude from 5,000 to 11,000 feet above the sea, but the lines of drainage are much lower, and the streams run at the bottoms of deep gorges or cañons. The plateaus are terminated in part by cliffs, and the cañon walls are cliffs. Plateaus, cañons, and cliffs are the characteristic features. The chief mountains are of volcanic origin, and they are doubly conspicuous, since they not only constitute some of the loftiest points, but are exceptional to the general character of the topography.

The climate is extremely dry—so dry that agriculture is impossible without irrigation. Vegetation is scant, except upon the heights. Below 8,000 feet altitude it is too sparse to interfere with the examinations of the geologist, and there are vast stretches of absolutely naked rock. Travel is greatly obstructed, except along certain lines, by deep cañons which ramify through the plateaus, and the selection of routes for wagon-roads and railroads is a work of great difficulty.

All this description applies more especially to the southern portions of the district. North of the Uintah Mountains the streams flow in shallower and broader valleys, and are more sluggish. The Green river, the main artery of drainage, is there less deeply sunken in the plain than in its lower course, and all erosion by running water is hence less powerful. The profiles of the topography are more rounded, and accumulations of local drift and soil give rise to many grassy plains.

The only important economic mineral of the whole region is

* In defining the province in my report to Lieut. Wheeler (see U. S. Eng. Expl. and Sur. W. of the 100th mer., vol. iii, Geology, pp. 43 and 542) I have not included the portion south of the Uintah Mountains. I was not aware, at the time of writing, that the plateaus south of the Uintas were continuous with those of Wyoming, the Uinta uplift not extending eastward to the Park Mountains.

coal, and this, though unlimited in quantity, is now utilized only where the Pacific railroad affords a market. Mines of the precious metals are nearly unknown, and in default of these, which are the usual incentives to settlement in our arid territories, the region is chiefly uninhabited by the whites, and portions are even unexplored, except by the ubiquitous trapper and prospector, who make no record of their discoveries. Along the western margin are Mormon settlements. The market afforded by the Pacific railroad and its dependencies, has stimulated a little farming in Wyoming, and the same result has been wrought at the south, in Arizona and New Mexico, by a line of military posts. But in the center of the province one can find a spot that is more than one hundred miles from the nearest house, excepting only the ruined and abandoned dwellings of the Peublo Indians, who once peopled this forbidding land more densely than it is likely ever to be peopled again.

II. *How the material is exposed for study.*

As a field for the studies of the geologist, the Plateau Province offers valuable *matter* in an advantageous *manner*. Let us begin with the consideration of the manner.

First, the Climate. The air is so dry that, except on the heights and at the margins of springs and streams, there is no turf, no accumulation of humus, often no soil, and so little vegetation that the view is not obstructed. From a commanding eminence one may see spread before him, like a chart, to be read almost without effort, the structure of many miles of country, and in a brief space of time may reach conclusions, which, in a humid region, would reward only protracted and laborious observation and patient generalization. There is no need to search for exposures where everything is exposed. Dr. Newberry, speaking of one of the southern plateaus, says, "On our way to the Moqui villages we passed through a region singularly favorable for accurate geological investigation; where there is no vegetation to impede the view; where the strata are entirely undisturbed, and are cut by valleys of erosion, in the wall-like sides of which every inch of the series may be examined. In this journey we ascended in the geological scale from the summit of the Carboniferous to the base of the Cretaceous series. Of this interval there is no portion of which the exposures are not as complete as could be desired." (Geol. Ives' Exped., p. 77.)

This aridity is not peculiar to the Plateaus: it pertains to the Basin Ranges, and in a less degree to the Plains. But in the Ranges the most arid portions are the valleys between the mountain ridges, and these are filled with monotonous Quaternary gravels and clays, which hide all other beds, while the ranges themselves, which are of more interest to the geologist,

catch all the precipitation, and are in some degree clothed with verdure.

Second, the Drainage. The Plains and the Plateaus are alike drained by great rivers, which rise in lofty mountain regions, and traverse them on their way to the sea; but there the resemblance ceases. The rivers which cross the Plains flow over them in broad shallow valleys. The soft rocks of the intervening benches decay more rapidly than they are undermined, and their rounded outlines are clothed with soil. But the Colorado and its branches flow across the Plateaus in deeply carved, narrow cañons. Where the Green river, which is the main fork of the Colorado, enters the Uintah Mountains, it is 2,000 feet below the adjoining plateau, and where the Colorado leaves the Plateaus, it emerges from a gorge 4,000 feet deep. In the interval the current courses, almost without exception, between high cañon walls. Into this deep channel are gathered the waters of the uplands. Empowered by the rapidity of its descent, each tributary river has carved a cañon of its own, and so too has each branch and creek tributary to a river, until the whole tract is divided by a labyrinth of ramifying cañons. When the rain falls—for it does sometimes fall here—it flows down rapidly into the gorges, and washes with it the loosened particles of disintegrating rock. Then in time of flood the deepening waters, constrained to a narrow channel, rush forward with impetuous velocity and sweep out the detritus. The rocks of the upland are removed as fast as they decay, and soil cannot accumulate. Thus does thorough drainage conspire with aridity to prepare for the geologist a land of naked rock.

No less important to the student are the cañons themselves. They bear the same relation to a plain that geological cross-sections do to a geological map. They introduce in all categories of observation a third dimension, and enable the contemplation of all the phenomena of structure with reference to depth as well as length and breadth.

Third, Glacial drift and Lava-sheets. While these are, in themselves, fertile subjects of study, they are also obstructions to observation, in so far as they conceal other formations from view; and it is as obstructions that I here refer to them.

Moraines are unknown in the southern half of the Plateau province, and in the northern they are not found at a lower altitude than 7,500 feet. The few that exist pertain to what were local glaciers. There was no general ice-mantle. The southern limit of glacial phenomena is in north latitude 38° 30′, or about on the parallel of St. Louis. In the epoch of ice the climate of the Plateaus doubtless bore the same relation to that of the eastern seaboard that it does now. It was then, as now, a little colder than the latter, and a great deal drier; and it was its dryness which prevented, even at an altitude of some thou-

sands of feet, the accumulation of such a deluge of ice as visited the Atlantic seaboard in the same latitude. Only on the highest mountains was the winter's precipitation in excess of the summer's melting.

But while the mantling by glacial drift is inconsiderable, that by extravasated material is of great extent. Some of the largest continuous lava fields of our country belong to the Plateau region. A field in southern Utah stretches ninety miles from north to south and seventy miles from east to west; and the corresponding dimensions of one in New Mexico and Arizona are one hundred and seventy-five, and one hundred and forty miles. Almost coalescent with the latter is a third field which includes the San Francisco group of peaks in Arizona. Beneath these, and beneath minor floods of lava, are buried a tenth part of the sedimentary rocks of the Plateaus.

In brief, the strata of the Plateau region are exposed with exceptional thoroughness. They are indebted to a dry climate, in ancient and modern times, for the almost entire absence of glacial drift, and for the suppression of vegetation. They are indebted to peculiar conditions of drainage for their poverty of soil, talus, and local drift, and for a system of natural cross-sections. Their chief detraction is a mere restriction of their area of exposure by overlapping lavas.

III. *The material for study.*

It remains to consider the nature of the material which is so fully exhibited, and examine its claims to attention. It pertains chiefly to four departments of geological investigation, viz: Mountain building by displacement; Mountain building by eruption; Stratigraphy; and Erosion; and will be discussed under these heads, in the order indicated.*

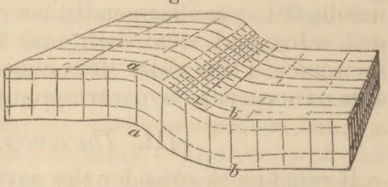
Mountain building by displacement. The Plateau Province differs from the mountain provinces by which it is surrounded in the degree and not in the kind of disturbance to which its sediments have been subject. Faults and folds abound through its whole extent, but they are comparatively of great simplicity.

* The writer traveled, during three summers, with field parties of the Survey in charge of Lieut. George M. Wheeler of the U. S. Engineers, and during a fourth with a field party of the Survey in charge of Major J. W. Powell. His reports to Lieut. Wheeler are published in the third volume of the reports of "Explorations and Surveys west of the 100th meridian." Besides his own observations, the chief sources from which he has derived the material here presented, are: 1. The observations of Major J. W. Powell, published in his report on the "Exploration of the Colorado River of the West and its tributaries;" and, in part, unpublished. 2 and 3. The observations of Mr. E. E. Howell and of the late Mr. A. R. Marvine, published in vol. iii, of Lieut. Wheeler's Reports, and in part unpublished. 4. The observations of Dr. J. S. Newberry, published in Ives' "Explorations of the Colorado," and in part unpublished. 5. The writings of Mr. Clarence King, "Fortieth Parallel Survey," vol. iii. 6. Mr. T. B. Comstock's report in the U. S. Engineers' "Reconnaissance of northwestern Wyoming." 7. Prof. E. D. Cope's report to Lieut. Wheeler, published in the U. S. Engineer report for 1875.

They are indeed so simple that they can be completely known. Their entire phenomena may be comprehended, measured, described, and delineated. The course of many a fault can be traced from end to end, and its throw measured at every step. The form of many a fold can be determined throughout, and pictured or modelled in miniature, with every detail of flexure.

Now, faults and folds are the *elements* of the displacements which give rise to mountains, and to study them is to study the very rudiments of mountain structure, and to acquire a knowledge of mountain structure is to lay the indispensable geological foundation for a true theory of the origin of mountains. Hence the value of this opportunity to study the elements of displacement in an uncombined condition, and in their simplest compound forms. To enforce this proposition, which is of more importance than might at first appear, I will take an illustration from the material already gathered, and, to do so, it will be necessary to explain one or two terms that have had to be coined to describe the new group of facts.

Fig. 1

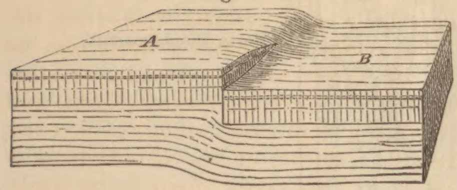


In an anticlinal fold the strata dip in two directions away from the axis. In a synclinal fold the strata dip from two directions toward the axis. There is in nature a third type, which involves a dip in only one direction. This is the *monoclinal* fold. It is a double flexure, connecting strata at one level with the same strata at another level. In figure 1, the curvature between *aa* and *bb* is a monoclinal fold.

It is evident that if two monoclinal folds are combined back to back, the result will be an anticlinal; if they are joined foot to foot, they will form a synclinal. Hence the monoclinal fold is a simpler element of displacement than either of the others.

When a portion of the earth's crust—it may be one that is measured by miles, or one that is measured only by feet—is moved bodily either up or down, while the portion adjacent to it is not so moved, the line along which they adjoin, will be marked by a fault, by a monoclinal fold, or by some combination of the two. The fault and the monoclinal fold are alternative manifestations of simple displacement, and are, in a certain sense, equivalent. There are several different ways in which they are combined with each other. If one travels along the line of displacement that separates two blocks of strata which stand at different levels, he may find that at one point the beds are continuous, and curve downward from the upper level to the lower; and that at another point they are broken across, and the dissevered edges have slidden past each other.

Fig. 2.



Or, if one could descend into the earth along the plane of dislocation, he might find that one stratum had been fractured, while another, less rigid, or coerced perhaps by a greater pressure of superincumbent rock, had been only flexed. A third mode of combination is exhibited when a bed yields at first by flexure, and is finally fractured before the completion of the dislocation. These phenomena are illustrated by figure 2, which is an ideal representation of two blocks of strata, *A* and *B*, cut out from their surroundings, so as to exhibit the manner of their relative displacement. The front of the segment shows a flexed bed underlying a faulted one. The top of the segment shows a fault at the front, a monoclinal fold at the back, and a compound displacement midway.

The monoclinal fold is not unknown in other parts of the world, but it has attracted little attention, and I am not aware that it has been described as abundant in any region. But in the region of the Plateaus it is not merely a feature of occasional occurrence; it is a characteristic type of displacement, and is rivalled in frequency only by the fault.

Let us now turn from the displacements, to the disturbed masses of rock which they divide. A fault or a monoclinal fold is merely the record, at the margin of a solid block, of a movement that has affected the entire block, and it bears the same subsidiary relation to the movement of the block, that a line bears to the angle or area which it limits and defines. A large portion of the Plateau region is divided into great blocks —usually a few miles in width and many miles in length—and these have been unequally lifted above the ocean which deposited their common sediments, so that each differs from its neighbor in altitude. They are bounded by lines of displacement. The blocks which have been lifted highest have been most exposed to erosive agencies, the tendency of which is to pare away eminences and reduce all to a common level: but as a rule, the highest plateaus mark the positions of blocks that have risen above their neighbors. The forms of many blocks are perfectly portrayed in the topography, and all can readily be traced out and defined by the study of the displacements.

In illustration I have borrowed, through the kindness of Major Powell, a wood-cut from the report of his "Exploration of the Colorado," and if the reader will examine it attentively, he will obtain a clearer idea of the structure I have described, than I can hope to convey in words. The sketch is not an ideal one, but was carefully drawn to represent a tract of

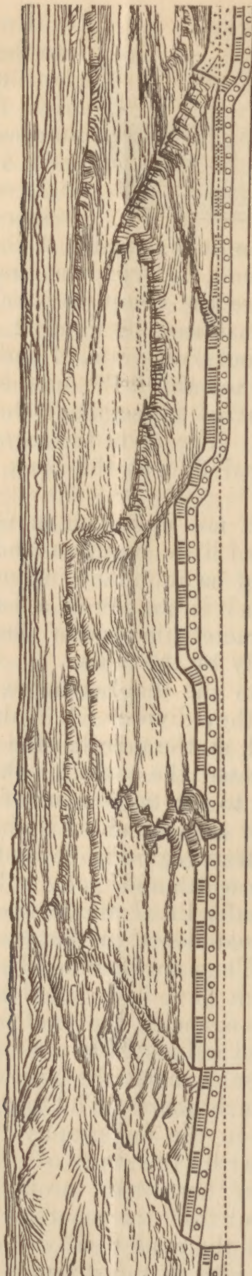


Fig. 3. Section from west to east across the plateaus north of the Grand Cañon of the Colorado, with bird's-eye view above. Horizontal scale, 16 miles to the inch; vertical scale, 4 miles to the inch. The base line marks the level of the ocean; the dotted line above it the level of the river.

country, lying in Utah and Arizona, of which the main geological features are clearly understood. The geological section in the foreground is, in the main, the section which is exposed in the walls of the Grand Cañon, and is 106 miles long. The vertical scale is four times as great as the horizontal. The base line marks the level of the ocean, and the dotted line the level of the Colorado river. The rock bed marked with small circles stands for the Lower Aubrey Group, a member of the Carboniferous System ; the one above it for the Upper Aubrey Group, also Carboniferous, and the dotted stratum, seen at the right, is the so-called Trias. In the bird's-eye view beyond the section, the foreground is of plateaus floored by the limestone of the Upper Aubrey, and beyond rise terraces built of Triassic and more recent strata. Five displacements are exhibited. Beginning at the left: the Hurricane displacement is a fault where it is intersected by the section, and has a throw of 2,500 feet Seventy miles farther north it is a combination of fault and fold. The throw of the To-ro′-weap fault is only 800 feet, and it disappears altogether in a few miles. The West Kai′-bab displacement is a monoclinal fold as far as it appears in the sketch, but farther south it changes to a fault. Its throw is 2,000 feet. The East Kaibab displacement is a double monoclinal fold in the foreground but a single one in the distance. Its total throw is 3,000 feet. The throw of the Paria displacement is 1800 feet. It is known only as a simple fold. Along the lines of the first three displacements the eastern wall has risen, or the western has fallen ; but with the remaining two the reverse is the case.

Between the Hurricane and Torroweap faults is contained the U′-in-ka-ret block. It is tilted slightly toward the east and is fifteen miles broad. Upon it stands a group of volcanic mountains, the lavas of which have risen through fissures in the block. Between the Toroweap and West Kaibab displacements is the Kan-ab′ block, thirty miles broad. It appears level in the east-west section, but has, in common with all the other blocks of the sketch, a gentle dip to the north. Its cap of Carboniferous limestone is divided in the foreground by the cañon of Kanab creek, and fifty miles away it passes beneath Triassic sandstones. The Kaibab block stands highest of all. The strata, which for fifteen miles run level on its summit, are flexed downward at both margins, on one side to the Kanab block, and on the other to the Marble Cañon block. Its upper surface is the Kaibab Plateau. The Marble Cañon block is thirty miles broad. On the line of the section its highest bed is of Carboniferous age, but a few miles farther north it retains a heavy bed of Trias, which rises 2000 feet higher and constitutes the Paria Plateau.

The features of the region pictured to which I wish especially to call attention, are:

First, that there are no anticlinals and no synclinals, but only monoclinals and faults;

Second, that the throws of the displacements are not all on the same side;

Third, that the visible portion of the earth's crust is divided into great blocks, which have changed their relative and absolute altitudes by thousands of feet, without losing their individuality.

The structure of this region is an unusually pure example of a type that, with various modifications, prevails throughout the Plateau region, and Major Powell has taken a name from the locality and called it the *Kaibab structure.* We cannot study the embryology of mountains by observing the progress of an individual, but it is possible, by the comparison of many individuals in various stages of development, to learn something of the manner of mountain growth, and, studying the subject in this way, the conclusion has been reached that many mountain ranges are built upon the plan of the Kaibab Plateau. The essential feature of the plan is the upward movement *en masse* of a great body of rock between two planes of displacement. A *plateau* is thus produced, from which mountain forms are carved by the ordinary processes of erosion. Evidences of such a plan have been found in nearly all the mountains of the upper basin of the Sevier River, in some of the ranges of the Great Basin, by Major Powell in the Uintah range, and by Mr. Marvine in the Front and Medicine Bow ranges of Colorado. Few of these cases are so simple as that of the Kaibab Plateau. In some the block has been lifted more on one side than on the other, so as to acquire a dip; in other cases there are a number of blocks of different elevation in the same range; in yet other, the blocks are somewhat curved.

I shall not attempt to enumerate the variations of the type, which arise in these several ways. The purpose of the illustration is accomplished, if I have shown that the exceptional exhibition, in the Plateaus, of displacements which are simple and easy of comprehension, has already led to the recognition of a new class of mountain structures, or at least of a class so little known heretofore that it has not found place in the manuals of geology.

When the displacements of the region have all been worked out, it will be possible to construct a model which shall exhibit the structure of at least one hundred and fifty thousand square miles of the earth's crust, showing the form and position of each of the blocks which compose it; and I conceive that such a model, or an equivalent presentation of the same material by some other method, will not be inferior in value to any single contribution that has been made to our knowledge of the results of orographic movements.

Mountain building by eruption.—The studies, which the Plateaus afford in the phenomena of eruption, are scarcely less interesting and important than those of uplift and downthrow; but they have received less attention up to the present time. It happens that a number of extinct eruptive mountains stand near the cañons of the Colorado River. The country about them has suffered and is suffering rapid denudation, and not only are their bases nearly free from detritus, but their flanks are so deeply scored, and their summits are so degraded, that their internal structure is exhibited. Those that are best known have been found to be composed chiefly of sedimentary strata, protected from denudation by the superior durability of the eruptive rocks with which they are associated.

In the U′-in-ka-ret mountains Major Powell found a mass of undisturbed strata, which had been preserved from erosion by a mantle of lava, while the surrounding country was degraded more than a thousand feet. The eruptions were extended through a long period of time, and the successive outflows mantled the flanks of the surviving strata almost as thoroughly as they did the summit, so as to give the appearance, at first glance, of a range made up entirely of volcanic matter.

In the Henry Mountains the strata are not undisturbed, but have been lifted into a number of bubble-shaped domes, one for each individual mountain of the group. Each dome has been fractured at top, and divided by fissures radiating from the center toward the sides, and all the fissures have been filled by molten rock. Moreover the strata have in many places cleaved apart, and lava sheets have been interleaved with them.

Doubtless the intrusion of these dikes and sheets was accompanied by extrusion, but none of the extruded masses appear to have survived the subsequent erosion. The mountains as they stand are simply domes of curved strata, each traversed by a plexus of crystalline dikes.

Similar in structure to the Henry Mountains are Navajo Mountain, Sierra la Sal, and Sierra Ábajo. Mount San Francisco, and perhaps Mount Taylor, are related to the Uinkarets. This enumeration includes but a small portion of the volcanic mountains of the district, and to the two types of structure mentioned, several others might be added. But the mountains of the Uinkaret and Henry types are most favorably situated for study, and at the same time diverge most widely in character from those with which geologists are already familiar.

Stratigraphy.—In the stratigraphy of the Plateaus attention has thus far been confined to questions that are chiefly of local importance, but a thorough study of the phenomena which are accessible can hardly fail to throw light on the

principles of sedimentation. In the region of cañons a single bed can be followed, upon one continuous outcrop, for hundreds of miles, and every modification that it undergoes can be traced step by step. Moreover, by reason of the ramifications of cañons, it is frequently possible to trace a bed toward all points of the compass, so as to learn its changes, not merely along a simple line, but throughout an extended area. With such exposures, unconformity cannot escape detection, and the history of a system of sediments can be made out with a completeness that surely cannot be excelled elsewhere.

Part II. Erosion.

It remains to indicate the scope of the material bearing upon the subject of erosion, and with that intent I will discuss certain problems which the region has propounded. The first may be called

The Problem of the Cañons.

The deep gorges which so facilitate the examination of the strata and of their displacements, are themselves of interest as monuments of erosion. To account for their existence and unravel their history is to review the laws of erosion with great wealth of illustration. Results so extreme can have been produced only under conditions equally extreme; and natural laws are often best tested and exemplified by the consideration of their operation under exceptional circumstances. Already the problem of the cañons has been attacked, and I cannot better demonstrate its radical value than by presenting the present aspect of the case. For this purpose it is necessary to give a summary statement of the processes of erosion and of the conditions which determine its rate. The matter is so complex that this cannot be done briefly without the omission of the less important factors, and in undertaking it I shall take the liberty of either disregarding or slighting all considerations which have not an important bearing on the problem in question.

In order to analyse sub-aerial erosion, we must consider it (A) as consisting of parts, and (B) as modified by conditions.

A. All indurated rocks and most earths are bound together by a force of cohesion, which must be overcome before they can be divided and removed. The natural processes by which the division and removal are accomplished make up erosion. They are called disintegration and transportation.

Transportation is chiefly peformed by running water.

Disintegration is naturally divided into two parts. So much of it as is accomplished by running water is called corrasion, and that which is not, is called weathering.

Stated in their natural order, the three general divisions of the process of erosion, are (1) *weathering*, (2) *transportation*, and (3) *corrasion*. The rocks of the general surface of the land are disintegrated by *weathering*. The material thus loosened is *transported* by streams to the ocean or other receptacle. In transit it helps to *corrade* from the channels of the streams other material, which joins with it to be transported to the same goal.

(1.) In weathering the chief agents of disintegration are solution, change of temperature, the beating of rain, and vegetation.

The great solvent of rocks is water, but it receives aid from some other substances, of which it becomes the vehicle. These substances are chiefly products of the formation and decomposition of vegetable tissues. Some rocks are disintegrated by their complete solution, but the great majority are divided into grains by the solution of a portion; and fragmental rocks usually lose by solution the cement merely, and are thus reduced to their original, incoherent condition.

The most rigid rocks are cracked by sudden changes of temperature; and the crevices thus begun, are opened by the freezing of the water within them. The coherence of the more porous rocks is impaired and often destroyed by the same expansive force of freezing water.

The beating of the rain overcomes the feeble coherence of earths, and assists solution and frost by detaching the particles which they have partially loosened.

Plants often pry apart rocks by the growth of their roots, but their chief aid to erosion is by increasing the solvent power of percolating water.

(2.) A portion of the water of rains flows over the surface and is quickly gathered into streams. A second portion is absorbed by the earth or rock on which it falls, and after a slow underground circulation reissues in springs. Both transport the products of weathering, the latter carrying dissolved minerals, and the former chiefly undissolved.

Transportation is also performed by currents of air, and by the direct action of gravity; but in the present discussion it will not be necessary to consider these accessory agents.

(3.) In corrasion the agents of disintegration are solution and mechanical wear. Wherever the two are combined, the superior efficiency of the latter is evident; and in all fields of rapid corrasion the part played by solution is so small that it may be disregarded.

The mechanical wear of streams is performed by the aid of hard mineral fragments which are carried along by the current.

The effective force is that of the current; the tools are mud, sand, and bowlders. The most important of them is sand; it is chiefly by the impact and friction of grains of sand that the rocky beds of streams are disintegrated.

Streams of clear water corrade their beds by solution. Muddy streams act partly by solution, but chiefly by attrition.

Streams transport the combined products of corrasion and weathering. A part of the debris is carried in solution, and a part mechanically. The finest of the undissolved detritus is held in suspension; the coarsest is rolled along the bottom; and there is a gradation between the two modes. There is a constant comminution of all the material as it moves, and the work of transportation is thereby accelerated. Bowlders and pebbles, while they wear the stream-bed by pounding and rubbing, are worn still more rapidly themselves. Sand grains are worn and broken by the continued jostling, and their fragments join the suspended mud. Finally the detritus is all more or less dissolved by the water, the finest the most rapidly.

In brief, (1) weathering is performed by solution; by change of temperature, including frost; by rain beating; and by vegetation.

(2) Transportation is performed chiefly by running water.

(3) Corrasion is performed by solution, and by mechanical wear.

Corrasion is distinguished from weathering chiefly by including mechanical wear among its agencies, and the importance of the distinction will be apparent when we come to consider how greatly and peculiarly this agency is affected by modifying conditions.

In the region of cañons, the progress of corrasion has outstripped that of weathering, and to discover what conditions have determined this result, is to solve the problem of the cañons.

B. The chief conditions which affect the rapidity of erosion are (1) declivity, (2) character of rock, and (3) climate.

(1.) In general, *erosion is most rapid where the slope is steepest;* but weathering, transportation and corrasion are affected in different ways and in different degrees.

With increase of slope goes increase in the velocity of running water, and with that goes increase in its power to transport undissolved detritus.

The ability of a stream to corrade by solution is not notably enhanced by great velocity; but its ability to corrade by mechanical wear keeps pace with its ability to transport, or may even increase more rapidly. For not only does the bot-

tom receive more blows in proportion as the quantity of transient detritus increases, but the blows acquire greater force from the accelerated current, and from the greater size of the moving fragments. It is necessary, however, to distinguish the ability to corrade from the rate of corrasion, which will be seen further on to depend largely on other conditions.

Weathering is not directly influenced by slope, but it is reached indirectly through transportation. Solution and frost, the chief agents of rock decay, are both retarded by the excessive accumulation of disintegrated rock. Frost action ceases altogether at a few feet below the surface, and solution gradually decreases as the zone of its activity descends and the circulation on which it depends becomes more sluggish. Hence the rapid removal of the products of weathering stimulates its action, and especially that portion of its action which depends upon frost. If, however, the power of transportation is so great as to remove completely the products of weathering, the work of disintegration is thereby checked; for the soil, which weathering tends to accumulate, is a reservoir to catch rain as it reaches the earth, and store it up for the work of solution and frost, instead of letting it run off at once unused.

In brief, a steep declivity favors transportation and thereby favors corrasion. The rapid, but partial, transportation of weathered rock accelerates weathering; but the complete removal of its products retards weathering.

(2.) Other things being equal, *erosion is most rapid when the eroded rock offers least resistance;* but the rocks which are most favorable to one portion of the process of erosion, do not necessarily stand in the same relation to the others. Disintegration by solution depends in large part on the solubility of the rocks, but it proceeds most rapidly with those fragmental rocks of which the cement is soluble, and of which the texture is open. Disintegration by frost is most rapid in rocks which absorb a large percentage of water and are feebly coherent. Disintegration by mechanical wear is most rapid in soft rocks. Transportation is most favored by those rocks which yield by disintegration the most finely comminuted debris

(3.) The influence of climate upon erosion is less easy to formulate. The direct influences of temperature and rainfall are comparatively simple, but their indirect influence, through vegetation, is complex, and is in part opposed to the direct influence of rainfall.

Temperature affects erosion chiefly by its changes. Where the range of temperature includes the freezing point of water, frost contributes its powerful aid to weathering; and it is only where changes are great and sudden that rocks are cracked by their unequal expansion or contraction.

All the processes of erosion are affected directly by the amount of rainfall, and by its distribution through the year. All are accelerated by its increase and retarded by its diminution. When it is concentrated in one part of the year at the expense of the remainder, transportation and corrasion are accelerated, and weathering is retarded.

Weathering is favored by abundance of moisture. Frost accomplishes most when the rocks are saturated; and solution, when there is the freest subterranean circulation. But when the annual rainfall is concentrated into a limited season, a larger share of the water fails to penetrate, and the gain from temporary flooding does not compensate for the checking of all solution by a long dry season.

Transportation is favored by increasing water supply as greatly as by increasing declivity. When the volume of a stream increases, it becomes at the same time more rapid, and its transporting capacity gains by the increment to velocity as well as by the increment to volume. Hence the increase in power of transportation is more than proportional to the increase of volume.

It is due to this fact chiefly, that the transportation of a stream which is subject to floods is greater than it would be if its total water supply were evenly distributed in time.

The indirect influence of rainfall and temperature, by means of vegetation, has different laws. Vegetation is intimately related to water supply. There is little or none where the annual precipitation is small, and it is profuse where the latter is great and especially where the temperature is at the same time high, In proportion as vegetation is profuse the solvent power of percolating water is increased, and, on the other hand, the ground is sheltered from the mechanical action of rains and rills. The removal of disintegrated rock is greatly impeded by the conservative power of roots and fallen leaves, and a soil is invariably preserved. Transportation is retarded. Weathering by solution is accelerated up to a certain point, but in the end it suffers by the clogging of transportation. The work of frost is nearly stopped as soon as the depth of soil exceeds the limit of frost action. The force of rain-drops is expended on foliage. Moreover a deep soil acts as a distributing reservoir for the water of rains, and tends to equalize the flow of streams.

Hence the general effect of vegetation is to retard erosion; and since the direct effect of great rainfall is the acceleration of erosion, it results that its direct and indirect tendencies are in opposite directions.

In arid regions of which the declivities are sufficient to give thorough drainage, the absence of vegetation is accompanied by

absence of soil. When a shower falls, nearly all the water runs off from the bare rock, and the little that is absorbed is rapidly reduced by evaporation. Solution becomes a slow process for lack of a continuous supply of water, and frost accomplishes its work only when it closely follows the infrequent rain. Thus weathering is retarded, and transportation has its work so concentrated by the quick gathering of showers into floods, as to compensate, in part at least, for the smallness of the total rainfall from which they derive their power.

Hence in regions of small rainfall, surface degradation is usually limited by the slow rate of disintegration; while in regions of great rainfall it is limited by the rate of transportation. There is probably an intermediate condition, with moderate rainfall, in which a rate of disintegration greater than that of an arid climate is balanced by a more rapid transportation than consists with a very moist climate, and in which the rate of degradation attains its maximum.

Having examined the conditions of erosion separately, let us now group them in such combination as will help to an understanding of the cañons.

Over nearly the whole of the earth's surface there is a soil, and wherever this exists we know that the conditions are more favorable to weathering than to transportation. Hence it is true in general that the conditions which limit transportation are those which limit the general degradation of the surface.

To understand the manner in which this limit is reached, it is necessary to look at the process by which the work is accomplished.

Transportation and Comminution.—A stream of water flowing down its bed expends an amount of energy that is measured by the quantity of water and the vertical distance through which it descends. If there were no friction of the water upon its channel the velocity of the current would continually increase; but if, as is the usual case, there is no increase of velocity, then the whole of the energy is consumed in friction. The friction produces inequalities in the motion of the water, and especially induces subsidiary currents more or less oblique to the general onward movement. Some of these subsidiary currents have an upward tendency, and by them is performed the chief work of transportation. They lift small particles from the bottom and hold them in suspension while they move forward with the general current. The finest particles sink most slowly and are carried farthest before they fall. Larger ones are barely lifted, and are dropped at once. Still larger are only half lifted; that is, they are lifted on the side of the current and rolled over,

without quitting the bottom. And finally there is a limit to the power of every current, and the largest fragments of its bed are not moved at all.

There is a definite relation between the velocity of a current and the size of the largest bowlder it will roll. It has been shown by Hopkins that the weight of the bowlder is proportioned to the sixth power of the velocity. It is easily shown also that the weight of a suspended particle is proportioned to the sixth power of the velocity of the upward current that will prevent its sinking. But it must not be inferred that the total load of detritus that a stream will transport bears any such relation to the rapidity of its current. The true inference is, that the velocity determines the limit in coarseness of the detritus that a stream can move by rolling, or can hold in suspension.

Every particle which a stream lifts and sustains is a draft upon its energy, and the measure of the draft is the weight (weighed in water) of the particle, multiplied by the distance it would sink in still water in the time during which it is suspended. If, for the sake of simplicity, we suppose the whole load of a stream to be of uniform particles, then the measure of the energy consumed in their transportation, is their total weight multiplied by the distance one of them would sink in the time occupied in their transportation. Since fine particles sink more slowly than coarse, the same consumption of energy will convey a greater load of fine than of coarse.

Again, the energy of a clear stream is entirely consumed in friction on its bottom; and the friction bears a direct relation to its velocity. But if detritus be added to the water, then a portion of its energy is diverted to the transportation of the load; and this is done at the expense of the friction upon the bottom, and hence at the expense of velocity. As the energy expended in transportation increases, the velocity diminishes. If the detritus be composed of uniform particles, then we may also say that as the load increases, the velocity diminishes. But the diminishing velocity will finally reach a point at which it can barely transport particles of the given size, and when this point is attained, the stream has its maximum load of detritus of the given size. But fine detritus requires less velocity for its transportation than coarse, and will not so soon reduce the current to the limit of its efficiency. A greater per cent of the total energy of the stream can hence be employed by fine detritus than by coarse.

Thus the capacity of a stream for transportation is enhanced by comminution in two ways. Fine detritus, on the one hand, consumes less energy for the transportation of the same weight, and on the other, it can utilize a greater portion of the stream's energy.

It follows, as a corollary, that the velocity of a fully loaded stream depends (*ceteris paribus*) on the comminution of the material of the load. When a stream has its maximum load of fine detritus, its velocity will be less than when carrying its maximum load of coarse detritus; and the greater load corresponds to the less velocity.

It follows also that a stream which is supplied with heterogeneous debris will select the finest. If the finest is sufficient in quantity, the current will be so checked by it, that the coarser cannot be moved. If the finest is not sufficient, the next grade will be taken, and so on.

Transportation and Declivity.—To consider now the relation of declivity to transportation we will assume all other conditions to be constant. Let us suppose that two streams have the same length, the same quantity of water, flow over beds of the same character, and are supplied to their full capacities with detritus of the same kind; but differ in the total amount of fall. Their declivities, or rates of fall, are proportional to their falls. Since the energy of a stream is measured by the product of its volume and its fall, the relative energies of the two streams are proportional to their falls, and hence, proportional to their declivities. The velocities of the two streams, depending as we have seen above, on the character of the detritus which loads them, are the same; and hence the same amount of energy is consumed by each in friction on its bed. And since the energy which each stream expends in transportation is the residual after deducting what it spends in friction from its total energy, it is evident that the stream with the greater declivity will not merely have the greater energy, but will expend a less per cent of it in friction and a greater per cent in transportation.

Hence declivity favors transportation in a degree that is greater than its simple ratio.

[There are two elements of which no account is taken in the preceding discussion, but which need to be mentioned to prevent misapprehension, although they detract in no way from the conclusions.

The first is the addition which the transported detritus makes to the energy of the stream. A stream of water charged with detritus is at once a compound and an unstable fluid. It has been treated merely as an unstable fluid requiring a constant expenditure of energy to maintain its constitution; but looking at it as a compound fluid, it is plain that the energy it developes by its descent, is greater than the energy pertaining to the water alone, in the precise ratio of the mass of the mixture to the mass of the simple water.

The second element is the addition which the detritus makes to the friction of the stream. The coefficient of friction of the compound stream upon its bottom will always be greater than that of the simple stream of water, and hence for the same velocity a greater amount of energy will be consumed.

It may be noted in passing, that the energy which is consumed in the friction of the detritus on the stream bed, accomplishes as part of its work the mechanical corrasion of the bed.]

Transportation and quantity of water.—The friction of a stream upon its bed depends on the character of the bed, on the area of the surface of contact, and on the velocity of the current. When the other elements are constant, the friction varies directly with the area of contact. The area of contact depends on the length and form of the channel, and on the quantity of water. For streams of the same length, and same form of cross-section, but differing in size of cross-section, the area of contact varies directly as the square root of the quantity of water. Hence, *cæteris paribus*, the friction of a stream on its bed, is proportioned to the square root of the quantity of water. But, as stated above, the total energy of a stream is proportioned directly to the quantity of water. And also, the total energy is equal to the energy spent in friction, plus the energy spent in transportation. Whence it follows, that if a stream change its quantity of water without changing its velocity or other accidents, the total energy will change at the same rate as the quantity of water, the energy spent in friction will change at a less rate, and the energy remaining for transportation will change at a greater rate.

It follows, as a corrollary, that the running water which carries the debris of a district, loses power by subdivision toward its sources; and that, unless there is a compensating increment of declivity, the tributaries of a river will fail to supply it with the full load which it is competent to carry.

It is noteworthy also, that the obstruction which vegetation opposes to transportation, is especially effective in that it is applied at the infinitesimal sources of streams, where the force of the running water is least.

A stream which can transport debris of a given size, may be said to be *competent* to such debris. Since the maximum particles which streams are able to move are proportioned to the sixth powers of their velocities, competence depends on velocity. Velocity, in turn, depends on declivity and volume, and (inversely) on load.

In brief, the capacity of a stream for transportation is greater for fine debris than for coarse.

Its capacity for the transportation of a given kind of debris is enlarged in more than simple ratio by increase of declivity; and it is enlarged in more than simple ratio by increase of volume.

The competence of a stream for the transport of debris of a given fineness, is limited by a correspondent velocity.

The *rate* of transportation of debris of a given fineness, may equal the capacity of the transporting stream, or it may be less. When it is less, it is always from the insufficiency of supply. The supply which is furnished by weathering is never available unless the degree of fineness of the debris brings it within the competence of the stream at the point of supply.

The chief point of supply is at the very head of the flowing water. The rain which falls on material that has been disintegrated by weathering, begins, after it has saturated the immediate surface, to flow off. But it forms a very thin sheet; its friction is great; its velocity is small; and it is competent to pick up only particles of exceeding fineness. If the material is heterogeneous, it discriminates and leaves the coarser particles. As the sheet moves on, it becomes deeper, and soon begins to gather itself into rills. As the deepening and concentration of water progresses, either its *capacity* increases and the load of fine particles is augmented, or, if fine particles are not in sufficient force, its *competence* increases, and larger ones are lifted. In either case the load is augmented, and, as rill joins with rill, it steadily grows, until the accumulated water finally passes beyond the zone of disintegrated material.

The particles which the feeble initial currents are not competent to move, have to wait either until they are subdivided by the agencies of weathering, or until the deepening of the channels of the rills so far increases the declivities, that the currents acquire the requisite velocity, or until some fiercer storm floods the ground with a deeper sheet of water.

Thus rate of transportation, as well as capacity for transportation, is favored by fineness of debris, by declivity, and by quantity of water. It is opposed chiefly by vegetation, which holds together that which is loosened by weathering, and shields it from the agent of transportation in the very place where that agent is weakest.

When the current of a stream gradually diminishes in its course—as, for example, in approaching the ocean—the capacity for transportation also diminishes; and so soon as the capacity becomes less than the load, precipitation begins,—the coarser particles being deposited first.

Corrasion.—If a stream has no load of detritus, it corrades only by solution. If it is loaded to its full capacity, it does

not corrade; it is on the verge between corrasion and deposition. Only with a partial load does a stream wear its bottom.

The rapidity of mechanical corrasion depends on the hardness, size, and number of transient fragments, on the hardness of the rock-bed, and on the velocity of the stream. The blows which the moving fragments deal upon the stream-bed are hard, in proportion as the fragments are large and the current is swift. They are most effective when the fragments are hard and the bed-rock is soft. Their number is increased, up to a certain limit, by the increase of the load of the stream; but when the fragments become greatly crowded at the bottom of a stream, their force is partially spent among themselves, and the bed-rock is in the same degree protected. For this reason, and because increase of load causes retardation of current, it is probable that the maximum work of corrasion is performed when the load is far within the transporting capacity.

The element of velocity is of double importance, since it determines, not only the speed, but, to a great extent, the size of the pestles which grind the rocks. The coefficients upon which it in turn depends, namely, declivity and quantity of water, have the same importance in corrasion that they have in transportation.

Let us now direct our attention to the region of the cañons.

The Plateau province lay beneath the ocean up to the close of the Mesozoic age. In early Cenozoic time it was nearly covered by fresh-water lakes, and was not greatly elevated.

In more recent epochs it has been very greatly, but unequally lifted, and the lakes have been drained. The erosion which began with the first lifting of a part above the ocean, and extended its area as the lakes disappeared, has progressed continually to the present time. The average total uplift has been about 12,000 feet; the mean altitude of the present surface is about 7,000 feet; and the difference is the mean amount of degradation. While 5,000 feet have been removed from the general surface, an amount greater by several thousand feet has been corraded by the rivers.

The greater tributaries of the Colorado have their sources in elevated mountains which are well supplied with rain. Their courses through the Plateaus traverse regions characterized by aridity.

On the uplands which border the cañons the supply of water is so small and the declivity is so great that weathering is less favored than transportation. No soil accumulates; vegetation is scant; and, for the lack of these, weathering is reduced to a minimum. The degradation of the surface is limited by the retarded weathering.

In the cañons corrasion is favored by a quantity of water which belongs to the mountain sources of the streams and not to the plateaus which they divide. It is favored by a great declivity of bed, for which it is indebted to the magnitude and recency of the uplift. It is favored by a moderate supply of debris, always sufficient for the work of excavation, but not so great as to consume the entire energy of the current.

The contrast between the degradation of the upland and the cutting of the water ways is strongest where the rocks are best fitted to resist disintegration. The rivers sink their channels into the land in a harmonious and interdependent system, and cannot excavate soft beds more deeply than hard. But the only downward limit to the degradation of the tables is the level of the draining river system; and the varying retardation which it suffers from the resistance of different rocks, is expressed in the varying height of the cañon walls.

A second problem which has arisen in the study of the erosion of the Plateaus may be called

The Problem of Waterfalls.

Where rivers descend a slope that is terraced by the alternation of hard and soft strata, they are apt to leap from the edges of the hard beds in waterfalls. But the Colorado, notwithstanding the structure of its bed presents the most favorable conditions, makes no leap. At the head of Marble Cañon, for instance, the river crosses a great bed of limestone, lying nearly level and underlaid by a great bed of friable sandstone. The limestone resists all erosive agents as strongly as does the Niagara limestone, and the sandstone yields to them as easily as does the Niagara shale. But, instead of plunging from one to the other in a great cataract, the Colorado cuts the two with nearly equal grade of channel. Its average descent in the hard rock is ten feet to the mile, and in the soft, less than five feet.

It is evident that for the production of waterfalls some condition is involved beside that of the constitution of the rock-system which the stream traverses,—some condition that pertains to the constitution of the stream itself. Such a condition is to be found in the relation of corrasion to transportation.

Let us suppose that a stream, endowed with a constant supply of water, is at some point continuously supplied with as great a load as it is capable of carrying. For so great a distance as its velocity remains the same, it will neither corrade nor deposit, but will leave the grade of its bed unchanged. But if in its progress it reaches a place where a less declivity of bed gives a diminished velocity, its capacity for transportation will become less than the load, and part of the load will be depos-

ited. Or if in its progress it reaches a place where a greater declivity of bed gives an increased velocity, the capacity for transportation will become greater than the load, and there will be corrasion of the bed. In this way a stream, which has a supply of debris equal to its capacity, tends to build up the gentler slopes of its bed and cut away the steeper. It tends to establish a single, uniform grade.

Let us now suppose that the stream, after having obliterated all the inequalities of the grade of its bed, loses nearly the whole of its load. Its velocity is at once accelerated and corrasion begins through its whole length. Since the stream has the same declivity, and consequently the same velocity, at all points, its capacity for corrasion is everywhere the same. Its rate of corrasion, however, will depend on the character of its bed. Where the rock is hard, corrasion will be less rapid than where it is soft, and there will result inequalities of grade. But so soon as there is inequality of grade, there is inequality of velocity, and inequality of capacity for corrasion; and where hard rocks have produced declivities, there the capacity for corrasion will be increased. The differentiation will proceed until the capacity for corrasion is everywhere proportioned to the resistance, and no farther,—that is, until there is an equilibrium of action.

In general, we may say that a stream tends to equalize its work in all parts of its course. Its power inheres in its fall, and each foot of fall has the same power. When its work is to corrade and the resistance is unequal, it concentrates its energy where the resistance is great, by crowding many feet of descent into a small space; and diffuses it, where the resistance is small, by using but a small fall in a long distance. When its work is to transport, the resistance is constant, and the fall is evenly distributed by a uniform grade. When its work includes both transportation and corrasion, as is the usual case, its grades are somewhat unequal; and the inequality is greatest when the load is least.

The condition of the Colorado in respect to load, is midway between that of the Niagara and that of the Platte.

The water of the Niagara is nearly devoid of load. The lake of which it is the outlet gathers the detritus of all tributary streams, and only on the occasion of a great storm yields a small portion of it to the Niagara. The work of transportation is at a minimum, and the differentiation of slope dependent on rock structure reaches its maximum in a cataract.

The water of the Platte is supplied with all the load it can move. Major Powell, who has made a careful study of this river, ascribes its peculiar character to the fact that it flows through a region of unconsolidated strata. Its mean declivity

is as great as that of the Colorado, and it would have carved cañons of imposing depth, if only the material of its banks were sufficiently coherent to stand in walls. As it is, the loose sands of the bordering plains are washed and blown into the river, and, its energy being consumed in their transportation, the corrasion of its channel can proceed no faster than the general degradation of the plain. Having little work to perform beside the transportation of its load, it maintains an almost unvaried slope from the foot of the mountains to its mouth.

In that portion of the Colorado which is contained in the Plateau province, the load consumes a share of the energy of the stream and leaves to corrasion the remainder. The slopes of the stream-bed are varied, but not so greatly as those of the Niagara. Where the bed-rock is soft, the declivity is small. Where it is hard, the declivity is relatively great; but in the toughest hornblende rock the mean angle of slope does not exceed three degrees.

The Problem of Inconsequent Drainage.

There is a third problem of erosion now under investigation in the Plateaus that promises results of value and novelty. It was propounded by Major Powell, and is set forth on page 162, *et seq.*, of his "Exploration of the Colorado River." The question to be answered is: What is the relation of the drainage system of the Plateaus to the system of displacements? How far is it *consequent*, how far *antecedent*, how far *super-imposed?*

If a series of sediments, accumulated in an ocean or lake, be subjected to a system of displacements while still under water, and then be converted to dry land by elevation *en masse*, or by the retirement of the water, the rains which fall on it will inaugurate a drainage system perfectly conformable with the system of displacements. Streams will rise along the crest of each anticlinal, will flow from it in the direction of the steepest dip, will unite in the synclinals, and will follow them lengthwise. The axis of each synclinal will be marked by a watercourse; the axis of each anticlinal by a watershed. Such a system is said to be *consequent* on the structure.

If, however, a system of displacements affect a rock series after the series has become continental, it will have already acquired a system of waterways, and, unless the displacements are produced with unusual rapidity, the waters will not be diverted from their accustomed ways. The effect of local elevation will be to stimulate local corrasion, and each river that crosses an uplifted block will, inch by inch as the block rises, deepen its channel and valorously maintain its original course. It will result that the directions of the drainage lines will be

independent of the displacements. Such a drainage system is said to be *antecedent* to the structure.

There is one other case. Suppose a rock series that has been folded and eroded, to be again submerged, and to receive a new accumulation of unconforming sediments. Suppose further, that it once more emerges, and that the new sediments are eroded from its surface. Then the drainage system will have been given by the form of the upper surface of the superior strata, but will be independent of the structure of the inferior series into which it will descend vertically as the erosion progresses. Such a drainage system is said to be *super-imposed* upon the structure of the older series of strata.

A large share of the drainage of the Plateaus is not consequent. How much is super-imposed, and how much antecedent remains to be determined. With the solution of the problem are involved the determination of the antiquity and history of the Green and Colorado Rivers, and the physical history of the great Tertiary lakes; and we may hope that from its discussion will result the establishment of laws, by the aid of which it shall be possible, in other regions, to deduce facts of geological history from an examination of the relation of structure to drainage.

Summary.

The exposure of the rock structure in the Colorado Plateau province is exceptionally thorough. Soil and vegetation obstruct the view less than in other lands, and deep cañons exhibit natural sections in many directions.

The rock structure is simple but not the simplest. The strata have been displaced, but their displacement is so little complex that it can be clearly determined in kind and amount.

In virtue of the simplicity of structure and continuity of exposure, the geologist does not have to put fragmentary data together and grope for the general facts of which they form part, but is able to see all the parts combined in nature in visible wholes. Nothing need be left for doubtful interpretation where everything can be seen; and with the facts of structure conspicuous and beyond question, the mind is left free to search for causes.

The facilities for the study of single, simple displacements, isolated from other phenomena of the same order, are equalled by those for the study of eruptive mountains which are at once simple, isolated, and dissected by erosion.

To the student of stratigraphy are offered continuous exposures of great length.

To the student of erosion are exhibited the most distinguished monuments of its action; and he is given an opportu-

nity to partially isolate certain of the conditions which control the rapidity of erosive action, by viewing their influence where that influence is at a maximum.

No attempt has been made in this brief review to indicate the entire range of the subjects that will interest the geological student of the region. It was proposed rather to call attention to those categories of phenomena which give greatest promise of affording contributions to the body of principles which constitute the science of geology,—as distinguished from the phenomena which will merely enlarge the body of facts upon which its established principles are based. The progress of geological exploration has compassed so small a fraction of the earth's surface that the aspect of the science is modified, in greater or less degree, by the addition of each important mass of facts; and when the contribution from the Plateaus shall have been made, I am confident that its record will find a place in the history of geological progress.

Already the field has yielded to its students results which are new to them, and which are probably new to the world of science. Among them are a type of uplifted mountains, a type of eruptive mountains, a theory of waterfalls, and a classification of drainage systems.